GRASSROOTS JOURNALS

Grassroots Journal of Natural Resources, Vol.7 No.2 (August 2024)
ISSN: 2581-6853 | CODEN: GJNRA9 | Published by The Grassroots Institute
Website: https://grassrootsjournals.org/gjnr | Main Indexing: Scopus and WoS

ISSN 2581-6853 | 7(2) Aug 2024

M – 00406 | Research Article

Assessment of Spatiotemporal Trends in Rainfall and Rainfall Extremes in the Hyderabad City, India

Durgasrilakshmi Hari*[1], Ramamohan Reddy Kasa[2]
[1]Jawaharlal Nehru Technological University, Hyderabad; Vardaman College of Engineering, Hyderabad, India. Email: harisrilakshmi@gmail.com | ORCID: https://orcid.org/0000-0002-7210-5923
[2]C.V.R College of Engineering, Hyderabad, India. Email: kasarammohan@gmail.com
ORCID: https://orcid.org/0000-0002-7210-5923
**Corresponding author*

How to cite this paper: Hari, D. and Kasa, R.R. (2024). Assessment of Spatiotemporal Trends in Rainfall and Rainfall Extremes in the Hyderabad City, India. *Grassroots Journal of Natural Resources*, 7(2): 216-235. Doi: https://doi.org/10.33002/nr2581.6853.070211

Received: 18 June 2024
Reviewed: 13 July 2024
Provisionally Accepted: 15 July 2024
Revised: 18 July 2024
Finally Accepted: 21 July 2024
Published: 01 August 2024
Copyright © 2024 by author(s)

Publisher's Note: We stay neutral with regard to jurisdictional claims in published maps, permissions taken by authors and institutional affiliations.

This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).
http://creativecommons.org/licenses/by/4.0/

Open Access

Executive (Chief) Editor
Dr. Hasrat Arjjumend
Associate Editors
Dr. Usongo Patience
Ms. Areej Sabir
This article is edited by Dr. Hasrat Arjjumend

Abstract

Rainfall is a crucial climate variable, shows irregular spatial and temporal variations. Significant spatial variability and persistent changes in land use intensify the complexity of urban weather systems. Therefore, climatological rainfall variables deserve attention from both a scientific and technological perspective. The rapid urban expansion of Hyderabad city, coupled with extreme weather variations, has led to increased environmental vulnerability. The present study aims to assess the spatiotemporal trends of annual rainfall and rainfall extremes in Hyderabad city from 1990 to 2020. This study employed the RClimDex model and daily gridded rainfall data to analyze annual rainfall and rainfall extreme indices, focusing on Consecutive Dry Days (CDD), Consecutive Wet Days (CWD), Total Precipitation (PRCPTOT), Rainfall Events Exceeding 10 mm (R10MM), 20 mm (R20MM), Total Precipitation from Very Wet Days (R95PTOT), Maximum 1-Day Precipitation (RX1DAY), and Maximum 5-Day Precipitation (RX5DAY). The trends in annual rainfall and rainfall extremes were assessed using the Mann-Kendall (MK) test, and spatial distribution variations for the identified trends were evaluated with the Inverse Distance Weighting (IDW) interpolation technique. The results of the study showed that no significant annual rainfall trends from 1990 to 2020, indicating natural variability rather than consistent long-term changes. However, extreme Consecutive Dry Days and Maximum Wet Spell trends show increasing trends. The PRCPTOT pattern remains almost stable, and R10MM rainfall events exhibit an increasing trend at a few locations, suggesting potential shifts in precipitation patterns. Conversely, a decreasing trend for rainfall extremes R20MM, R95PTOT, RX1DAY, and RX5DAY indicate a general reduction in extreme rainfall events and very wet days in GHMC suggesting localized reductions in extreme events and varied impacts of prolonged rainfall reductions at annual scale. The study reveals Hyderabad's high spatial variability in annual rainfall distribution and rainfall extremes, emphasizing the importance of analyzing high resolution gridded rainfall data for effective decision-making and efficient water resource management.

Keywords

Rainfall; Rainfall extremes; Trend; Mann-Kendall; Spatial; Interpolation

Introduction

In the hydrological cycle, rainfall is a significant climatic element by enabling water to move and change between the major components of the Earth's surface (Islam *et al*., 2012). The rainfall distribution over time and space directly affects the water resources quantity and quality within a watershed (Adarsh and Reddy, 2015). Significant rainfall variability across spatial and temporal scales, potentially linked to urbanization, has major implications for urban development and planning, particularly in conjunction with climate change as well as rapid urbanization (Mohammed, Regonda and Kopparthi, 2022). Extreme events driven by climate change, can further worsen the uneven distribution of rainfall. It is crucial to consider these factors when developing strategies for climate adaptation and resilience to ensure the sustainable water management in view of a climate change. Thus, effective water resource management strategies require knowledge of rainfall and rainfall extremes nature in a specific region. Trend analysis through statistical techniques is becoming ever more popular throughout the years, specifically when assessing rainfall spatial and temporal variability (Bambang *et al.*, 2023).

Globally, studies employing the Mann-Kendall (Mann, 1945; Kendall, 1975) test have highlighted diverse trends of rainfall and extreme events. The Mann-Kendall test, a non-parametric test widely used to assess trends in climatic and hydrological data, has been instrumental in understanding these changes. Several studies have utilized the Mann-Kendall test to analyze trends in rainfall and extremes across different parts of India (Bambang *et al.*, 2023; Deka *et al*., 2016; Jenifer and Jha, 2021; Jyostna *et al*., 2022; Kumar, 2021; Rao *et al*., 2020; Sharma *et al*., 2018; Waghaye *et al*., 2018). In addition, Kumar, Jain and Singh (2010) examined long-term trends in monsoon rainfall using the Mann-Kendall test and identified significant regional differences. The study provided important insights about spatial and temporal rainfall trends in India, emphasizing the importance of understanding regional variations for effective resource management and policy-making. Subash, Sikka and Ram Mohan (2011) applied the Mann-Kendall test to analyze trends in extreme rainfall indices over India. Their findings indicated significant trends in extreme rainfall events, particularly in central and southern regions. These results underscore the importance of understanding regional rainfall trends to inform water resource management and disaster preparedness. Gajbhiye *et al*. (2016) provides a comprehensive analysis of rainfall trends in the Sindh River basin, revealing both increasing and decreasing trends in annual rainfall across different stations. Most of the stations showed no significant trend, indicating stable long-term rainfall patterns, while some stations exhibited spatial variability in seasonal rainfall. Rao *et al*. (2020) analyzed rainfall and rainfall extremes variability and spatio-temporal trends within Nagavali and Vamsadhara river Basins in India, identifying significant alterations in magnitude and rate of extremes over the years, particularly in the monsoon season. Jyostna *et al*. (2022) highlighted considerable spatial variability in rainfall across Telangana state, India, with regions experiencing different trends influenced by geographical and climatic factors. Seasonal analysis showed variations in rainfall trends during different times of the year. Certain regions showed an increase in rainfall during the monsoon season, while others exhibited decreasing trends or no significant changes. Murali *et al*. (2022) analyzed long-term trends in precipitation over Telangana State, India, from 1901 to 2015. The analysis shown a spatially heterogeneous pattern in annual precipitation trends across different regions of Telangana. The Mann-Kendall test revealed a consistent positive trend in

annual rainfall data, with lower slopes in northern regions, and a significant positive trend during the monsoon and post-monsoon periods. Prabhu and Chitale (2024) reported that approximately 44% of Telangana's tehsils have seen an increase in rainfall attributed to the post monsoon (OND), which mainly affects peninsular India. These studies collectively emphasize the importance of trend analysis for understanding spatiotemporal variations of rainfall and rainfall extremes in developing effective strategies for climate adaptation and sustainable water management.

Hyderabad, a rapidly urbanizing city in India, faces unique challenges related to changing rainfall patterns and extremes. Extreme rainfall events frequently damage the city's infrastructure, resulting in floods and waterlogging. Understanding the spatiotemporal trends in rainfall and its extremes is crucial for developing effective water resource management and urban planning strategies within the Hyderabad city. The study by Agilan and Umamahesh (2015) analyzes non-stationarity in extreme rainfall events in Hyderabad, revealing an increasing trend in intensity and frequency with a 4.5% and 1% rise in sub-daily (4-hourly) extreme rainfall between 1-4 am and 5-8 am during non-monsoon months. The study suggests that global processes like the ENSO cycle and global warming are primarily responsible for the daily extreme rainfall, while local factors like urbanization and temperature changes contribute to the sub-daily extreme rainfall. Research by Singh, Khole and Rase (2015) indicates a significant increase in heavy rainfall events during the Southwest monsoon season, particularly in August in Hyderabad.

However, existing research often suffers from limitations due to missing data and insufficient high temporal and spatial resolution rainfall data over extended periods. This gap hinders the capture of detailed variability and trends essential for urban settings like Hyderabad. Mohammed, Regonda and Kopparthi (2022) conducted an event-based rainfall analysis using high-resolution hourly data from 37 Automatic Weather Stations (AWSs) in Hyderabad over 7 years (2013-2018), examining 118 rainfall events. The study identified distinct temporal rainfall patterns, with peaks during June to September.

Notably, short-duration, high-intensity rainfall events were prominent, especially in the oldest city region, which experienced higher rainfall frequency, depths, and intensities, with monsoon rains occurring in the evenings and midnights. Non-stationarity was observed with decreased inter-station association and increased rainfall activity compared to suburban areas. The study, even with limitations due to missing data and sampling issues, recommends continuous monitoring and analysis of high-resolution long-term rainfall data for better understanding and predicting rainfall patterns to differentiate them from natural climate variability. Despite these findings, there is still a pressing need for continuous monitoring and robust statistical analysis to understand long-term trends, changes, and rainfall variability characteristics. Addressing these issues is vital for informing effective urban planning, disaster management, and sustainable water management practices in Hyderabad. This study aims to bridge these critical gaps by providing a comprehensive analysis of rainfall and rainfall extremes using high-resolution data, ultimately supporting resilience strategies in the face of climate change.

Doi: https://doi.org/10.33002/nr2581.6853.070211 Open Access

Study Area

Hyderabad, the capital city of Telangana, India, is divided into several administrative regions. Greater Hyderabad Municipal Corporation (GHMC) is the primary administrative body responsible for governing the city of Hyderabad. It encompasses the core urban area of Hyderabad and consists of multiple zones and circles. The total area covered by GHMC is 650 square kilometers. Hyderabad receives 810.5 mm of rain annually on average and has an average yearly temperature of 26.7 °C. The city has experienced significant population growth over the years due to urbanization and economic opportunities. Several times in the past ten years in July 2012, September 2016, September 2019 Hyderabad and the surrounding areas have experienced significant rainfall events ranging between 15 and 24 cm in just one day. On October 13 and 14, 2020, the city experienced floods as a result of extreme rainfall up to 30 centimeters of rain in a single day (Rangari, Bhatt and Umamahesh, 2021). Before that, the maximum observed rainfall was 24 cm in 24 hours in August 2000.

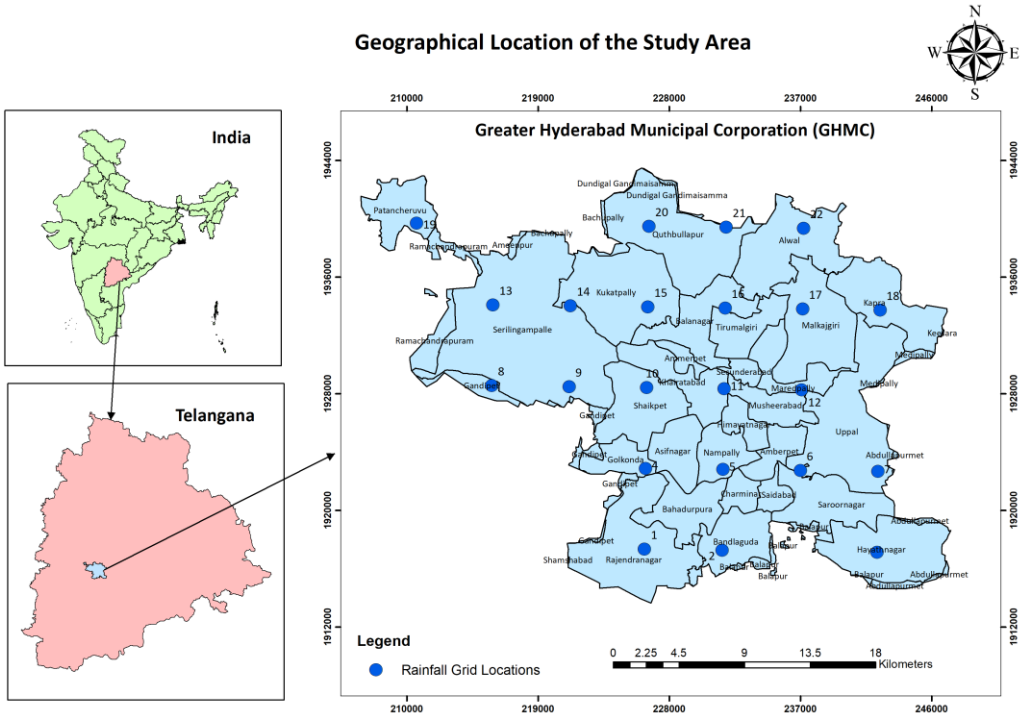

Figure 1: Geographical Location Map of the Study Area

These instances of extreme rainfall highlight the vulnerability of the region to heavy precipitation and the potential impact it can have on the local environment, infrastructure, and residents. Such heavy rainfall can lead to flooding, disruption of daily activities, damage to property, and pose risks to public safety. Robust statistical analysis of rainfall data enables the identification of long-term trends, changes, and rainfall variability characteristics. Statistical techniques, such as trend analysis, time series analysis, and frequency analysis, help quantify changes in rainfall patterns, including

shifts in intensity, duration, frequency, and seasonality. These analyses provide valuable insights into climate variability, potential climate change impacts, and sustainable water management practices. Gridded precipitation data provides information on rainfall patterns across a specific region, this data is often derived from various sources, such as rain gauges, weather stations, and satellite observations. By analyzing gridded data, one can identify the variations in rainfall across different locations within a catchment, helping to understand localized patterns and trends. Geographical location of the study area along with rainfall grid locations within GHMC considered for this study are represented in figure 1.

Data and Methodology

Data

Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) daily gridded rainfall data from the years 1990 to 2020 was taken from Climate Hazards Group website (https://www.chc.ucsb.edu/data/chirps). The CHIRPS dataset provides estimates of rainfall and related information globally. CHIRPS combines satellite imagery and ground station data to generate high-resolution rainfall data. It covers the entire globe, having spatial resolution of 5 km approximately. The CHIRPS rainfall data is widely used in various applications, including climate research, agriculture, hydrology, and disaster management. It provides valuable information on precipitation patterns, drought monitoring, and flood risk assessment (Funk *et al*., 2015).

Methodology

In the present analysis, using daily rainfall data, eight out of eleven rainfall extremes recommended by the CCI/WCRP/JCOMM Expert Team on Climate Change Detection and Indices (ETCCDI) at each grid location have been calculated on an annual scale. The analysis of these rainfall extremes over the GHMC will help assess the patterns and trends in rainfall extremes, providing valuable insights into changes in precipitation behavior and contributing to the understanding of climate change impacts. The details of rainfall extreme indices considered in the current study are presented in table 1.

Procedure for Calculating Rainfall Extremes

The RClimDex package in R (Bronaugh, 2019) software was used to calculate rainfall extremes for annual rainfall, which is maintained and created by Yang Fang and Xuebin Zhang at the Climate Research Division (CRD) or ETCCDI. This package is widely used to compute rainfall extremes as it ensures the accuracy and reliability of the results by performing basic quality check of input data prior to the calculations.

The rainfall data format for calculating the rainfall extreme indices should be in a plain text format, such as a .csv file, with columns for Year, Month, Day, and Precipitation. For an example to determine the number of Consecutive Dry Days (CDD) from the provided data (Table 2), the software will identify Dry days as days with precipitation less than 1mm. Next it will identify the longest sequence of Consecutive Dry Days.

In the present example the first sequence of dry days is from January 1 to January 3 (3 days) and the second sequence of dry days is from January 5 to January 9 (5 days). The calculation will confirm that the longest sequence of consecutive dry days (CDD) in the provided dataset is 5 days.

Table 1: Rainfall extreme indices considered in this study, which were developed by the ETCCDI

Index	*Description*	*Unit*	*Indicator*
CDD	Consecutive dry days (maximum number of consecutive days with daily precipitation < 1 mm)	days	Longest spell of dry days
CWD	Consecutive wet days (maximum number of consecutive days with daily precipitation ≥ 1 mm)	days	Longest spell of wet days
PRCPTOT	Annual total precipitation in wet days (days with daily precipitation ≥ 1 mm)	mm	Total rainfall in wet days
R10MM	Number of heavy precipitation days (days with daily precipitation ≥ 10 mm)	days	Count of heavy precipitation days
R20MM	Number of very heavy precipitation days (days with daily precipitation ≥ 20 mm)	days	Count of very heavy precipitation days
R95PTOT	Very wet days (annual total precipitation from (days > 95th percentile of daily precipitation)	mm	Total rainfall from very wet days
RX1DAY	Maximum 1-day precipitation amount	mm	Maximum rainfall in a single day
RX5DAY	Maximum consecutive 5-day precipitation amount	mm	Maximum rainfall over five consecutive days

Table 2: Rainfall Data format for calculating the Rainfall Extreme Indices

Year	*Month*	*Day*	*Precipitation*
1990	01	01	0.0
1990	01	02	0.0
1990	01	03	0.5
1990	01	04	1.2
1990	01	05	0.0
1990	01	06	0.0
1990	01	07	0.0
1990	01	08	0.0
1990	01	09	0.0

The Mann-Kendall (MK) Test

To detect the trends in time series data a non-parametric statistical test the Mann-Kendall (MK) test (Mann, 1945; Kendall, 1975) can be used. In the present study Mann-Kendall (MK) test is carried out using open-source software packages in R called "modifiedmk" (Patakamuri and O'Brien, 2020). This test is widely applied for hydrological and

climatological studies for assessing the presence and significance of trends in various environmental variables, including rainfall.

The time series data, daily gridded rainfall data, is organized in chronological order with equal time intervals (e.g., years, months, or days). Each data point represents a measurement of the variable of interest (rainfall) at a specific time. The Mann-Kendall (MK) test is calculated using the eq 1 to 7. If x_1, x_2, x_3, ……, x_n is the time series of length n, then the MK test statistics S is given as

$$S = \sum_{i=1}^{n} \sum_{j=i+1}^{n} sign(x_j - x_i) \quad (1)$$

$$\text{Where, } sign(x_j - x_i) = \begin{cases} 1 & if\ (x_j - x_i) > 0 \\ 0 & if\ (x_j - x_i) = 0 \\ -1 & if\ (x_j - x_i) < 0 \end{cases} \quad (2)$$

The hydrological time series dataset shows no trend, supporting the null hypothesis (H0). Hypothesis 1: The hydrological time series dataset exhibits a pattern that is either increasing or decreasing. Equation (1) provides the variance V(S) and mean E(S) of the statistic S, assuming that S is normally distributed.

$$E(S) = 0 \quad (3)$$

$$V(S) = \frac{n\,(n-1)(2n+S)}{18} \quad (4)$$

The MK standardized test statistics Z is given by

$$Z = \begin{cases} \dfrac{S-1}{(V(S))^{1/2}} & S > 0 \\ 0 & S = 0 \\ \dfrac{S+1}{(V(S))^{1/2}} & S < 0 \end{cases} \quad (5)$$

S values that are negative suggest a decreasing trend, and vice versa. The significance levels (SL) of rejecting the null hypothesis are provided by the test statistic Z. The confidence level (CL) in rejecting the null hypothesis is provided by

$$CL = 1 - SL \quad (6)$$

Analysis of Spatiotemporal Trends in Rainfall

In order to analyze spatiotemporal trends in rainfall and rainfall extremes the spatial interpolation of rainfall data is produced by means of Inverse Distance Weight (IDW) method in ArcGIS platform. This method allows for the interpolation of rainfall trends across Hyderabad city by estimating values at unmeasured locations based on the known values and their spatial proximity. The results of spatiotemporal patterns of rainfall extremes are analyzed to understand the characteristics, trends, and potential impacts of extreme rainfall events, which are crucial for climate adaptation, water resource management, and infrastructure planning.

Results and Discussion

Average Annual Rainfall

The annual average rainfall of GHMC in mm from 1990 to 2020 was calculated and presented in figure 2. The study area witnessed an increasing trend in annual average rainfall, with a minimum annual average rainfall of 616.06 mm in 2004 and a maximum annual average rainfall of 1362.04 mm in 2020. GHMC recorded a total annual average rainfall of 863.58 mm from 1990 to 2020.

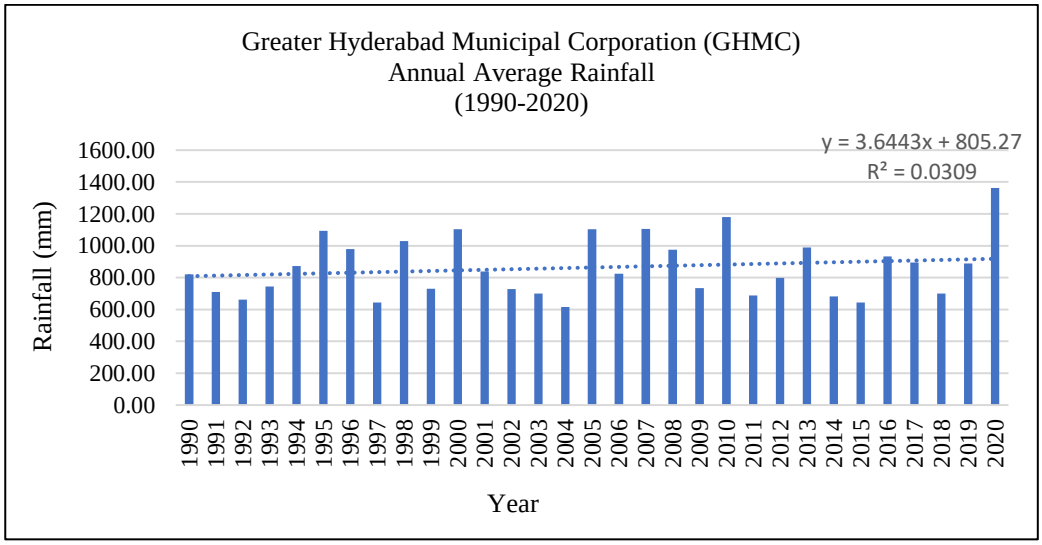

Figure 2: Annual Average Rainfall of GHMC in mm (1990-2020)

Rainfall Statistical Analysis

Rainfall statistical analysis was performed for the annual average rainfall of 22 locations from 1990 to 2020 in Hyderabad city. The Table 3 represents the location wise Min, Max, Annual Mean Rainfall, Standard Deviation (SD) in mm and Coefficient of Variation (CV%). Spatial distribution maps these statistical parameters are generated using IDW interpolation technique in ArcGIS software and are presented in figures 3 and 4.

GHMC has experienced annual average rainfall ranging from 841.76 mm to 885.29 mm across different areas, reflecting significant variation in rainfall intensities. The central, northeast, and southeast regions of the city have received higher rainfall compared to other areas. In contrast, the northwest, central, and southwest regions have seen lower average annual minimum rainfall, which ranges from 596.74 mm to 647.84 mm. On the other hand, the average annual maximum rainfall varies from 1307.83 mm to 1417.54 mm, with the northeast, southeast, and central regions receiving the highest amounts. The standard deviation of rainfall is an important measure for understanding rainfall variability over time. In GHMC, the standard deviation of average annual rainfall ranges from 226.29 mm to 313.02 mm, indicating considerable variability and unpredictability in rainfall patterns. The central and southern parts of the city show the greatest

Doi: https://doi.org/10.33002/nr2581.6853.070211 Open Access

fluctuations in rainfall, highlighting the importance of understanding these patterns for effective water resource management and urban planning.

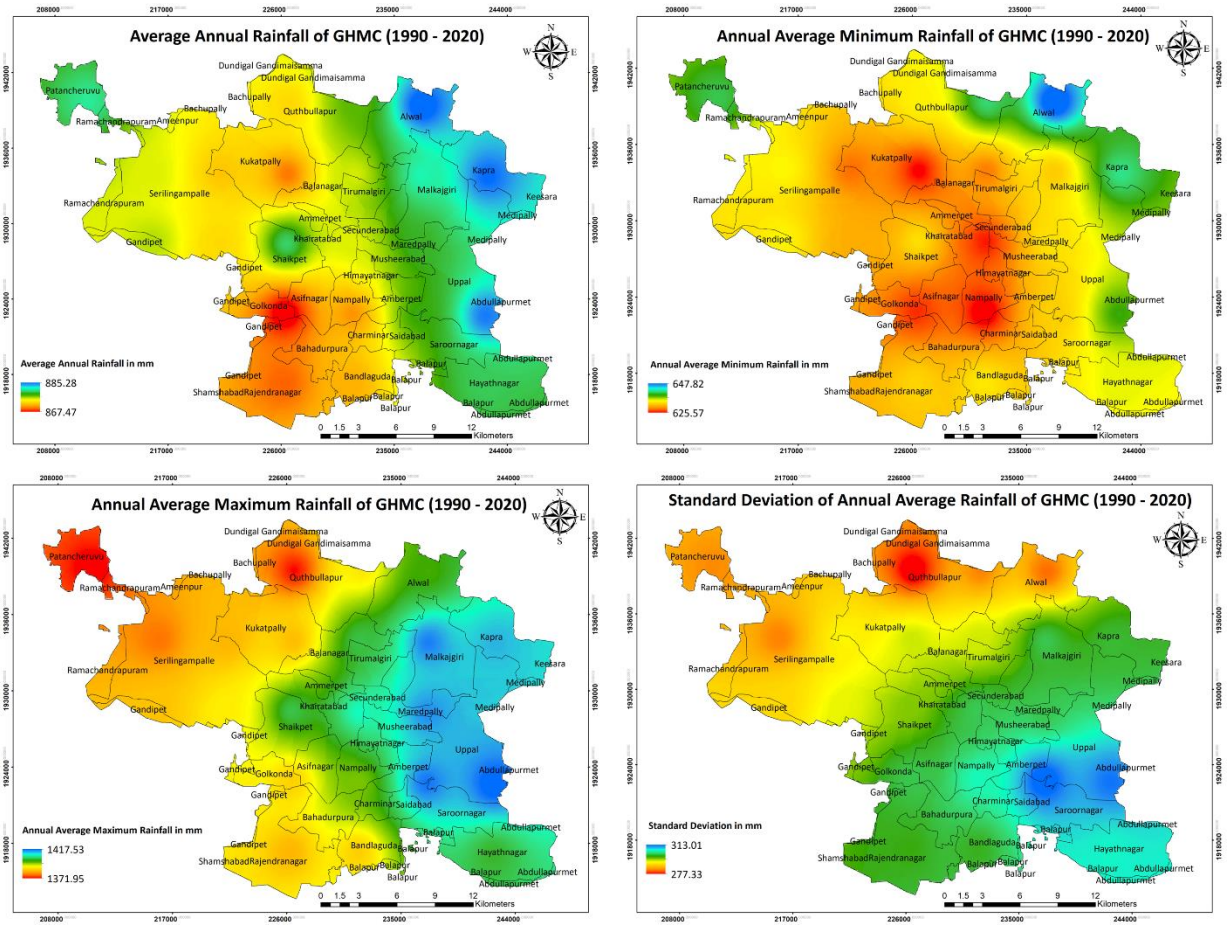

Figure 3: Spatial Distribution of Rainfall Statistical Parameters (Annual Average (MEAN), MIN, MAX, SD)

Table 3: Rainfall Statistical Analysis

Grid No.	*LAT*	*LONG*	*MIN*	*MAX*	*MEAN*	*SD*	*CV%*
1.	17.325	78.425	612.11	1333.71	847.83	277.55	32.74
2.	17.325	78.475	614.39	1339.75	852.65	278.62	32.68
3.	17.325	78.575	617.50	1375.31	870.85	293.69	33.72
4.	17.375	78.425	599.89	1340.24	841.76	283.15	33.64
5.	17.375	78.475	596.74	1364.74	850.87	292.00	34.32
6.	17.375	78.525	611.51	1412.10	867.66	313.02	36.08
7.	17.375	78.575	625.66	1417.54	882.28	308.27	34.94
8.	17.425	78.325	615.60	1337.08	862.48	254.29	29.48
9.	17.425	78.375	608.12	1347.44	856.49	263.49	30.76
10.	17.425	78.425	613.22	1378.84	871.47	271.38	31.14
11.	17.425	78.475	599.17	1391.86	860.91	283.49	32.93
12.	17.425	78.525	613.62	1407.93	868.44	283.04	32.59

Grid No.	*LAT*	*LONG*	*MIN*	*MAX*	*MEAN*	*SD*	*CV%*
13.	17.475	78.325	615.79	1322.43	860.89	241.19	28.02
14.	17.475	78.375	603.72	1333.53	854.52	260.10	30.44
15.	17.475	78.425	598.27	1335.78	849.25	265.71	31.29
16.	17.475	78.475	604.66	1378.48	861.29	265.10	30.78
17.	17.475	78.525	611.06	1410.54	874.59	283.10	32.37
18.	17.475	78.575	631.77	1402.41	883.32	280.61	31.77
19.	17.525	78.275	628.88	1307.83	873.54	242.43	27.75
20.	17.525	78.425	615.39	1310.11	856.38	226.29	26.42
21.	17.525	78.475	630.74	1346.51	866.00	241.78	27.92
22.	17.525	78.525	647.84	1370.67	885.29	238.87	26.98

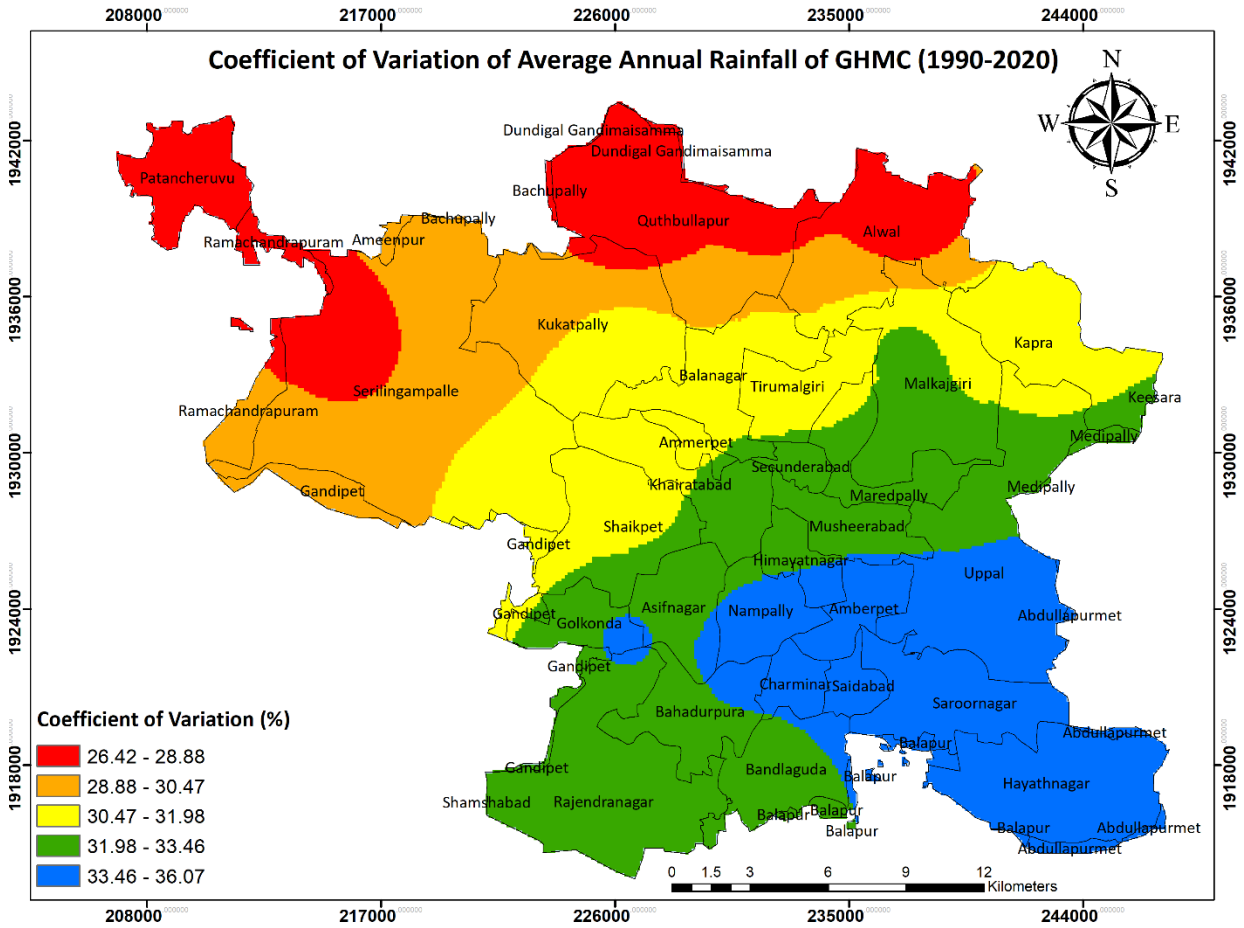

Figure 4: Spatial Distribution of Coefficient of Variation of Annual Average

The coefficient of variation (CV) can be employed to describe the spatial variability by comparing the standard deviation of rainfall amounts to the mean rainfall amount across different locations. Rainfall variability is divided into three categories: low (CV <20), moderate (20 < CV < 30), and high (CV >30) based on the CV values (Addisu *et al*., 2015). The coefficient of variation of average annual rainfall over GHMC area varied from 26.42 to 36.08. The statistical analysis shows that the annual CV% is having moderate to high

rainfall variability across the measured rainfall grid locations in the study area. The central and southern parts of the city exhibit high rainfall variability, with CV values greater than 30% indicates that the rainfall amounts can differ significantly from the average, pointing to more unpredictable rainfall patterns. In contrast, the northern parts of the city show moderate rainfall variability, with CV values between 20% and 30%.

Trends of Annual Rainfall and Rainfall Extremes

The Mann-Kendall (MK) test is used to examine annual trends in rainfall and rainfall extremes for 22 grids across the city of Hyderabad with a confidence level of 90% or above. Table 4 displays the Mann-Kendall Z statistics of annual rainfall and rainfall extremes trend analysis**.** Figures 5 and 6 depict the spatial distribution of trends in annual rainfall and rainfall extremes in GHMC, which have been mapped using the IDW interpolation method.

Table 4: Mann-Kendall Z statistics of annual rainfall and rainfall extremes trend analysis

Grid No.	*LAT*	*LON*	*ANNUAL*	*CDD*	*CWD*	*PRCPTOT*	*R10MM*	*R20MM*	*R95PTOT*	*RX1DAY*	*RX5DAY*
1	17.325	78.425	0.31	**1.85**	**2.68**	1.53	**1.65**	0.70	-0.12	0.00	0.31
2	17.325	78.475	0.37	**2.50**	**2.62**	1.56	1.50	0.71	-0.02	-0.92	0.34
3	17.325	78.575	0.34	**1.68**	**2.45**	**1.80**	**1.83**	1.01	-0.26	-1.33	0.07
4	17.375	78.425	0.2	**2.41**	**2.80**	0.07	-0.07	***-1.81***	***-1.85***	-0.58	***-1.67***
5	17.375	78.475	0.27	**1.89**	**2.79**	-0.14	0.46	***-2.13***	***-1.79***	-1.29	-1.36
6	17.375	78.525	0.54	**2.60**	**2.95**	-0.10	-0.07	***-2.01***	***-1.82***	-1.29	-1.39
7	17.375	78.575	0.41	**2.35**	**3.18**	-0.10	-0.22	***-2.29***	-1.61	-1.36	-1.33
8	17.425	78.325	0.48	-0.53	1.54	1.05	**1.70**	0.02	-0.95	-1.63	-0.14
9	17.425	78.375	0.54	-0.15	1.20	1.02	**1.81**	-0.14	-0.92	-1.63	-0.07
10	17.425	78.425	0.54	-0.09	**1.81**	1.22	**1.91**	0.34	-1.17	***-1.67***	-0.03
11	17.425	78.475	0.51	0.34	**2.36**	0.24	0.65	-0.89	-1.46	***-1.94***	***-2.92***
12	17.425	78.525	0.51	0.22	**1.82**	0.99	1.60	-0.22	***-1.67***	-1.56	-0.68
13	17.475	78.325	0.61	0.00	**2.76**	0.37	0.80	-0.29	-1.36	***-1.87***	-1.26
14	17.475	78.375	0.75	-0.39	**2.23**	0.68	0.00	-0.63	-1.50	-1.56	-1.16
15	17.475	78.425	0.92	-0.53	**2.20**	0.58	0.41	-0.67	-1.36	-1.33	-1.19
16	17.475	78.475	0.61	-0.37	**1.95**	0.54	0.55	-0.87	-1.00	***-1.70***	-1.19
17	17.475	78.525	0.68	-1.02	1.41	0.48	1.06	-1.06	-1.07	***-2.31***	***-1.67***
18	17.475	78.575	0.58	-0.61	1.54	0.20	0.53	-1.25	***-1.65***	***-1.94***	-1.33
19	17.525	78.275	0.85	**2.48**	**1.93**	-0.44	-0.43	-1.13	***-1.80***	***-2.48***	***-2.38***
20	17.525	78.425	0.75	-0.66	**1.98**	0.54	0.39	-0.82	-1.07	***-1.84***	-0.95
21	17.525	78.475	0.44	-0.68	1.62	0.37	0.03	-0.58	-1.46	-1.43	-0.65
22	17.525	78.525	0.44	0.24	**1.83**	0.68	0.38	-0.12	-0.87	-1.33	-0.51

Note: Bold number indicates significant trends confidence level at 90% ($Z \geq 1.65$) an increasing trend and Bold in Italic number indicates significant trends confidence level at 90% ($Z \leq -1.65$) a decreasing trend.

Trends in Annual Rainfall

The MK test results demonstrate that, out of the 22 rainfall grids analyzed from 1990 to 2020 in GHMC, no significant annual rainfall trends were identified at 90% confidence interval. The absence of significant trends implies that annual rainfall variations are likely

due to natural variability rather than any consistent long-term change. Urban planners and water managers should focus on the variability in rainfall extremes to ensure that infrastructure and resources are resilient to both droughts and heavy rainfall, even in the absence of significant annual trends. Continuous monitoring and adaptive planning are key to managing water resources effectively in the face of natural variability.

Trends in Rainfall Extremes

From the results, it is observed that the rainfall extreme Consecutive Dry Days (CDD) shows an increasing trend mostly in the southern parts of the city, including the mandals of Golkonda, Nampally, Saroornagar, Uppal, Rajendra Nagar, Bandlaguda, and Hayathnagar, as well as in the northwest part of Patancheruvu. The increasing trend in CDD indicates longer dry periods in these areas, necessitating robust water conservation and storage systems, such as rainwater harvesting and aquifer recharge, to manage extended dry spells.

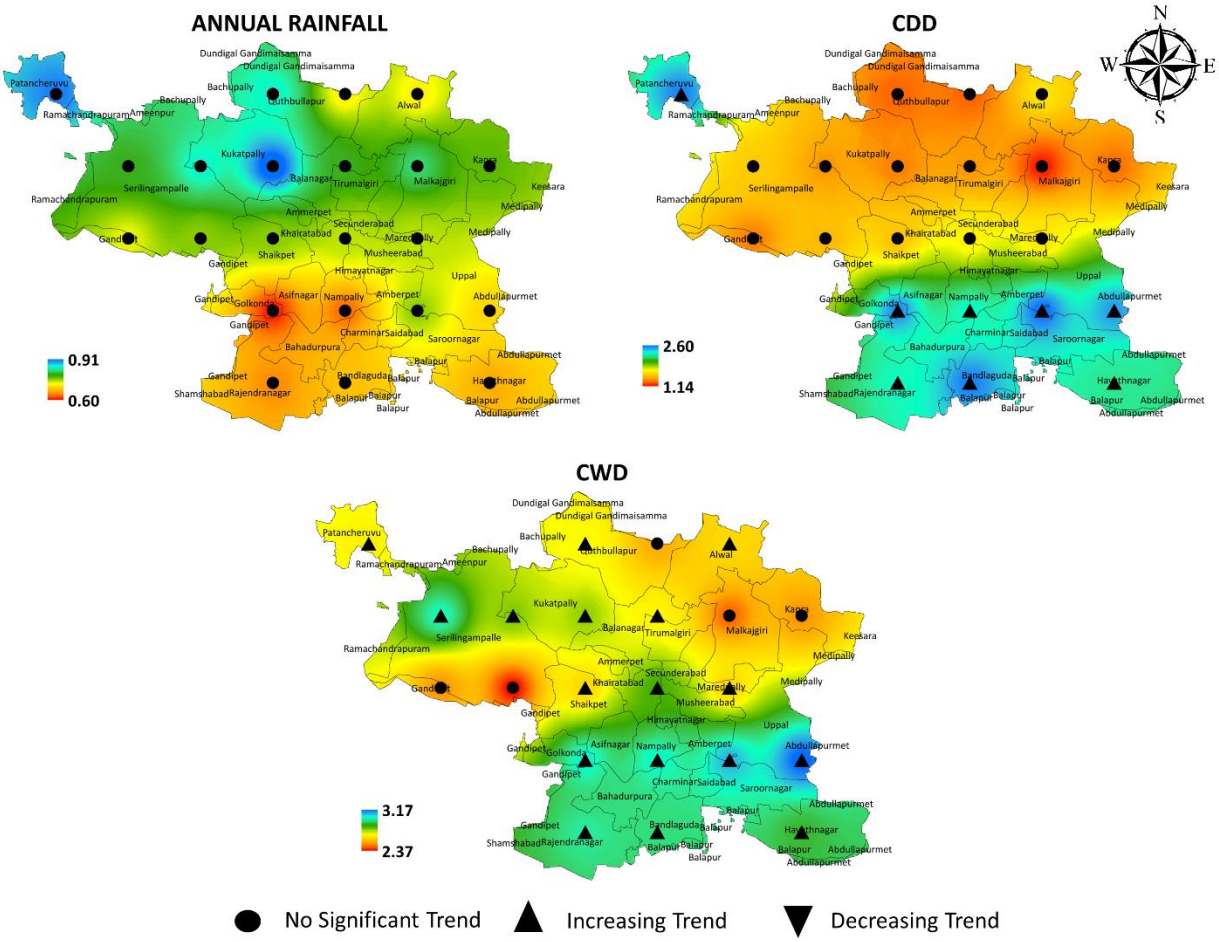

Figure 5: Spatial Distribution of Trends in Annual Rainfall and Rainfall Extremes (CDD, CWD)

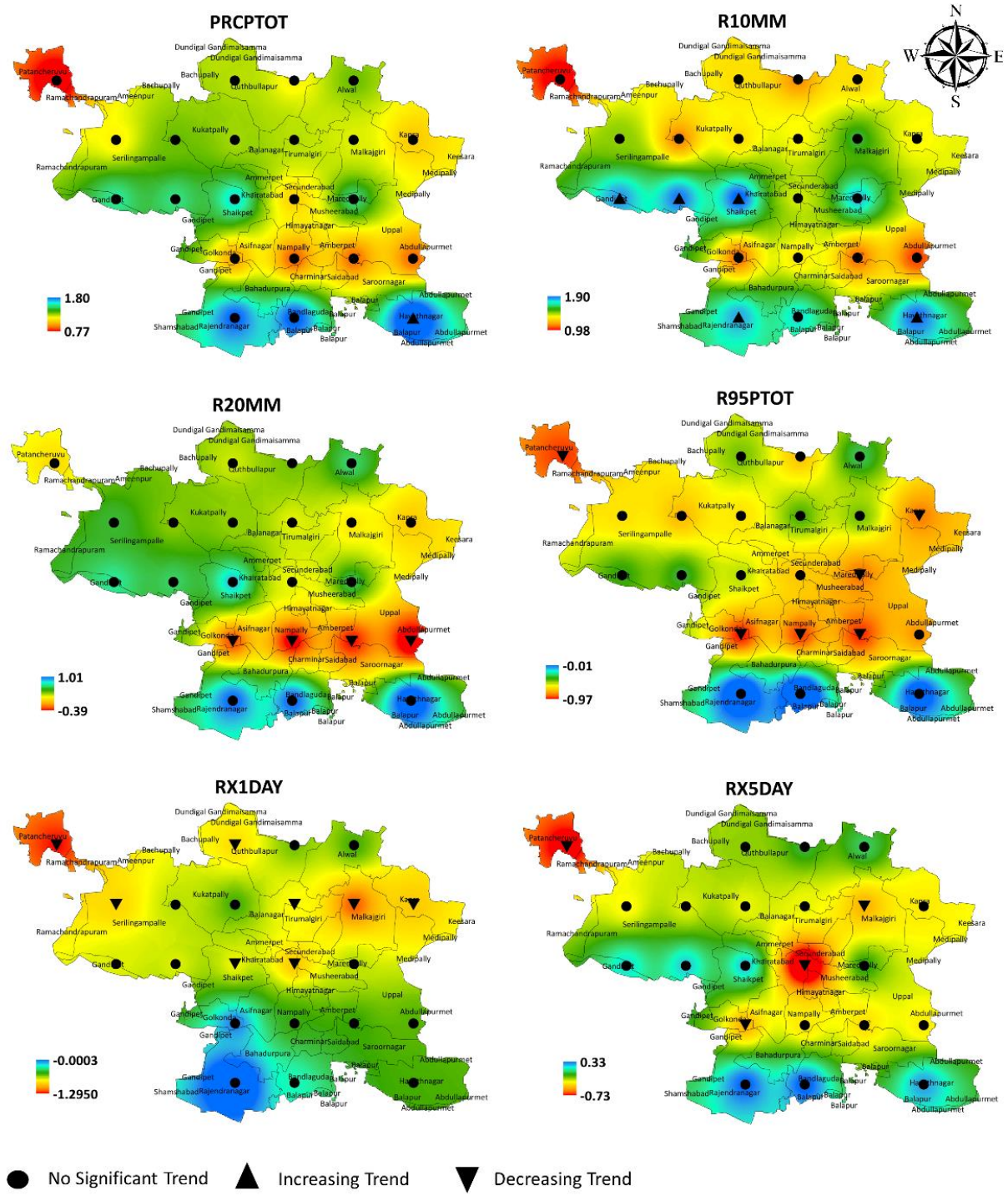

Figure 6: Spatial Distribution of Trends in Rainfall Extremes (PRCPTOT, R10MM, R20MM, R95PTOT, RX1DAY, RX5DAY)

Additionally, maintaining urban green spaces and tree cover is crucial for mitigating the heat island effect exacerbated by prolonged dry periods. The maximum length of wet spell, the Consecutive Wet Days CWD shows a significant increasing trend in the central and southern parts of the city, including Patancheruvu in the northwest, which are also well-distributed across the city except for Gandipet, Malkajgiri and Kapra mandals. The increasing trend in CWD, especially in central and southern parts of Hyderabad, shows longer continuous periods of rainfall indicating increasing durations of wet spells, necessitating enhanced drainage and storm water management systems to manage prolonged wet spells and prevent flooding. Upgrading drainage infrastructure and implementing sustainable urban drainage systems are vital, along with ensuring proper sewage and waste management. This analysis reveals distinct spatial trends in rainfall extremes; specifically, the consecutive dry days (CDD) and consecutive wet days (CWD) show significant and contrasting trends in different parts of Hyderabad. Both increasing CDD and C WD trends are observed in the southern parts of Hyderabad. This suggests that these areas experience more pronounced extremes, with longer dry spells (CDD) interspersed with longer wet spells (CWD). Mandals like Golkonda, Nampally, Saroornagar, Uppal, Rajendra Nagar, Bandlaguda, and Hayathnagar are experiencing both extremes, highlighting the variability and unpredictability in rainfall patterns. The central parts show a significant increasing trend in CWD, indicating longer periods of continuous rainfall. The presence of prolonged wet spells implies a marked variability, which could lead to subsequent dry periods. Whereas the regions of Gandipet in the west and Malkajgiri and Kapra in the east do not show significant trends for both extremes suggesting a more stable rainfall pattern. Patancheruvu mandal in the northwest shows an increasing trend in CDD and CWD, indicating longer dry periods interspersed with longer wet spells suggests that the area experience more pronounced extremes require a balanced approach to handle both extremes. The variation in these trends across different parts of the city highlights the need for location-specific strategies.

The results indicated consistent trends for Total Precipitation (PRCPTOT) across most grids, with a significant increasing trend identified in Hayathnagar mandal. This suggests that, on average, annual total rainfall has remained relatively stable over the three-decade period, except in Hayathnagar, where increased precipitation necessitates effective water management and flood control measures. An increasing trend was observed at five grid locations for Rainfall events exceeding 10 mm (R10MM), primarily in the central part of the city, including Gandipet, Serilingampalle, and Shaikpet, and in the southern regions of Rajendranagar and Hayathnagar mandals. This increase in moderate rainfall events suggests potential shifts in precipitation patterns, which can impact urban drainage, groundwater recharge, and localized flooding risks. The MK test detects a decreasing trend in rainfall events exceeding 20 mm (R20MM) at four grid points, predominantly in the southern region of Hyderabad located in the mandals of Golkonda, Nampally, Saroornagar, and Uppal. A reduction in heavier rainfall events exceeding 20 mm could impact groundwater recharge rates and ecosystem resilience in these areas. The MK test results for R10MM and R20MM in GHMC highlight contrasting trends in moderate and heavier rainfall events from 1990 to 2020. While R10MM shows an increasing trend in central and southern parts, R20MM exhibits a decreasing trend primarily in the southern region. These results highlight the significance of careful consideration of rainfall frequency in urban planning and water management methods in

order to improve Hyderabad's resilience to climate variability and ensure sustainable development practices.

The analysis showed a decreasing trend in Total Precipitation from Very Wet Days (R95PTOT) at six grid locations, including Golkonda, Nampally, and Saroornagar in the south, Maredpally in the central region, Kapra in the northeast, and Patancheruvu in the northwest. This could mean fewer instances of extreme rainfall events that significantly contribute to annual totals. Maximum 1-Day Precipitation (RX1DAY) measures the maximum precipitation that occurs in a single day, indicating the intensity of short-duration extreme events. RX1DAY shows a decreasing trend at eight grid locations. The affected mandals are Patancheruvu, Serilingampalle, Quthbullapur, Balanagar, Malkajgiri, and Kapra in the northern parts of GHMC, and Shaikpet and Khairatabad in the central regions. This decreasing trend suggests a reduction in the occurrence of extreme rainfall events over a single day. This could lead to a lower risk of flash floods and related urban flooding issues. Maximum 5-Day Precipitation (RX5DAY) captures the maximum precipitation over a 5-day period, reflecting the impact of prolonged heavy rainfall. RX5DAY shows a decreasing trend at four grid locations, including Patancheruvu in the northwest, Golkonda in the southwest, Khairatabad in the central part, and Malkajgiri in the northeast. The decreasing trend in maximum 5-day precipitation indicates fewer prolonged heavy rainfall events. This can reduce the likelihood of sustained flooding but may impact water storage and long-term water availability. All three indices (R95PTOT, RX1DAY, RX5DAY) at annual scale show decreasing trends in various parts of GHMC, indicating a general reduction in extreme rainfall events over the period of 3 decades. In R95PTOT decreasing trends are observed in both southern and northern parts of GHMC, indicating a widespread reduction in very wet days. For RX1DAY the decreasing trend is more concentrated in the northern and central parts, suggesting localized reductions in 1-day extreme events. And for RX5DAY the decreasing trend is spread across the northwest, southwest, central, and northeast regions, indicating varied impacts of prolonged rainfall reductions.

The trends of rainfall and rainfall extremes in Hyderabad city can be attributed to several factors, which include both natural climatic variability and anthropogenic influences. Topography can influence local climate and weather patterns. Removal of green cover can disrupt the local water cycle, reducing evapotranspiration and altering rainfall patterns. The expansion of urban areas leads to higher temperatures and urban heat island zones in cities which influences local weather patterns and increase the likelihood of intense rainfall events. Urbanization increases the number of impervious surfaces, reducing natural water absorption and increasing runoff. This can exacerbate the impact of heavy rainfall, leading to more extreme rainfall events and floods in Hyderabad city. Urban pollution can contribute to changes in local weather patterns, affecting rainfall distribution and intensity. Effective urban planning and climate adaptation strategies are essential to mitigate the adverse impacts of these changing rainfall patterns in Hyderabad city.

Conclusions

Overall, the study employs statistical techniques such as the Mann-Kendall test, combined with spatial interpolation using the IDW method, to analyze trends in annual rainfall and rainfall extremes in Hyderabad city from 1990 to 2020. The results shows

that an increasing trend for the rainfall extremes CDD, CWD, and R10MM, while a decreasing trend is noted for the rainfall extremes R20MM, R95PTOT, RX1DAY, and RX5DAY. No obvious trend is detected for PRCPTOT, except in one grid where it shows an increasing trend. There is notable spatial variability in rainfall distribution across Hyderabad, with some areas receiving significantly more rainfall than others. Certain areas within Hyderabad show increasing trends in rainfall intensity, while others exhibit stable or decreasing trends, highlighting localized climatic variations. The spatial heterogeneity in Hyderabad is influenced by local topography, land use changes, urbanization, and microclimatic conditions. These findings allow for the identification of significant trends and the assessment of spatial patterns of rainfall and rainfall extremes, providing valuable insights into the changing precipitation patterns in Hyderabad, which assists in planning and managing water resources. Future research could focus on analyzing monthly and seasonal rainfall trends and extremes, differentiating between monsoon and non-monsoon periods to better understand seasonal variability and its impacts. This could provide more detailed insights into short-term variations and help identify critical periods for rainfall extremes. Assessing the impact of the urban heat island effect on seasonal rainfall patterns and extremes, particularly during pre-monsoon and post-monsoon seasons, can provide insights into urban climate interactions.

To address the threats posed by extreme rainfall events in Hyderabad, a comprehensive strategy is required. Improved drainage infrastructure and implementing sustainable drainage systems can help manage runoff and reduce flooding risks. Incorporating climate resilience and flood management considerations into urban planning processes. Preserving and restoring natural water bodies and floodplains to facilitate natural water absorption and mitigate flood risks. Promoting green infrastructure, urban green spaces and rainwater harvesting can enhance city resilience to extreme rainfall events by absorbing rainwater. By implementing a multi-faceted strategy that combines infrastructure improvements, community engagement, and proactive planning, Hyderabad can enhance its resilience to extreme rainfall events and reduce the associated risks and impacts.

Acknowledgments

The authors extend their sincere gratitude to the Climate Hazards Center at the University of California, Santa Barbara for providing CHIRPS daily rainfall data, which significantly contributed to their research.

References

Adarsh, S. and Reddy, M.J. (2015). Trend analysis of rainfall in four meteorological subdivisions of southern India using nonparametric methods and discrete wavelet transforms. *Int. J. Climatol* 35: 1107-1124. DOI: https://doi.org/10.1002/joc.4042.

Addisu, S., Selassie, Y.G., Fissha, G. and Gedif, B. (2015). Time series trend analysis of temperature and rainfall in lake Tana sub-basin, Ethiopia. *Environmental Systems Research*, 4(25): 1-12. DOI: https://doi.org/10.1186/s40068-015-0051-0.

Agilan, V. and Umamahesh, N.V. (2015). Detection and attribution of non-stationarity in intensity and frequency of daily and 4-h extreme rainfall of Hyderabad. *India J. Hydrol*, 530: 677-697. DOI: http://dx.doi.org/10.1016/j.jhydrol.2015.10.028.

Bambang, I., Saravanan, S., Reddy, N.M. and Abijith, D. (2023). An investigation of the changing patterns of rainfall in the Indravathi subbasin utilizing the Mann–Kendall and Sen's slope methods. *IOP Conf. Ser.: Earth Environ. Sci*, 1173: 012036. DOI: https://doi.org/10.1088/1755-1315/1173/1/012036.

Bronaugh, D. (2019). Climdex.pcic: PCIC Implementation of Climex Routines. R package version 1.1-9.1. Available online at: https://CRAN.R-project.org/package=climdex.pcic (accessed on 11 June 2024).

Deka, R.L., Mahanta, C., Nath, K.K. and Dutta, M.K. (2016). Spatio-temporal variability of rainfall regime in the Brahmaputra valley of North East India. *Theor Appl Climatol*, 124: 793-806. DOI: https://doi.org/10.1007/s00704-015-1452-8.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. and Michaelsen, J. (2015). The climate hazards infrared precipitation with stations - a new environmental record for monitoring extremes. *Science Data*, 2: 150066. DOI: https://doi.org/10.1038/sdata.2015.66.

Gajbhiye, S., Meshram, C., Mirabbasi, R. and Sharma, S.K. (2016). Trend analysis of rainfall time series for Sindh River basin in India. *Theoretical and Applied Climatology*, 125*:* 593-608. DOI: https://doi.org/10.1007/s00704-015-1529-4.

Islam, T., Rico-Ramirez, M.A., Han, D., Srivastava, P.K. and Ishak, A.M. (2012). Performance evaluation of the TRMM precipitation estimation using ground-based radars from the GPM validation network. *J. Atmos. Sol.-Terr. Phys*, 77: 194-208. DOI: https://doi.org/0.1016/j.jastp.2012.01.001.

Jenifer M.A. and Jha, M.K. (2021). Assessment of precipitation trends and its implications in the semi-arid region of Southern India. *Environmental Challenges*, 5: 100269. DOI: https://doi.org/10.1016/j.envc.2021.100269.

Jyostna, B., Meena, A., Rathod, S., Tuti, M.D., Kallakuri, S., Bhanusree, D. and Reddy, B.N.K. (2022). Trend Analysis of Rainfall in Telangana State (India) Using Advanced Statistical Approaches. *International Journal of Environment and Climate Change*, 12(11): 3404–3412. DOI: https://doi.org/10.9734/ijecc/2022/v12i111391.

Kendall, M.G. (1975). *Rank Correlation Methods*, 4th Edition. London: Charles Griffin.

Kumar, A., Giri, R.K., Taloor, A.K. and Singh, A.K. (2021). Rainfall trend, variability and changes over the state of Punjab, India 1981–2020: A geospatial approach, *Remote Sensing Applications: Society and Environment*, 23: 100595. DOI: https://doi.org/10.1016/j.rsase.2021.100595.

Kumar, V., Jain, S. K., and Singh, Y. (2010). Analysis of long-term rainfall trends in India. *Hydrological Sciences Journal*, *55*(4): 484-496. DOI: https://doi.org/10.1080/02626667.2010.481373.

Mann, H.B. (1945). Nonparametric tests against trend. *Econometrica,* 13: 245-259. DOI: https://doi.org/10.2307/1907187.

Mohammed, A., Regonda, S.K. and Kopparthi, N.R. (2022). Climatological features of high temporal resolution rainfall over the Hyderabad city, India. *Urban Climate*, 42: 101118. DOI: https://doi.org/10.1016/j.uclim.2022.101118.

Murali, A., Rangarajan, S., Thattai, D., Kamaraj, M., Varadharajan, D., Bhutia, S.Y. and Islam, M.N. (2022). Trend Analysis of Precipitation (1901–2015) over Telangana

State, India. *In:* Islam, M.N. and Amstel, A.V. (eds.), *India II: Climate Change Impacts, Mitigation and Adaptation in Developing Countries*. *Cham.: Springer*, pp.351-382. DOI: https://doi.org/10.1007/978-3-030-94395-0_15.

Patakamuri, S.K. and O'Brien, N. (2020). Modified Versions of Mann Kendall and Spearman's rho Trend Tests. R Package Version 1.6. Available online at: https://CRAN.R-project.org/package=modifiedmk (accessed on 15 June 2024).

Prabhu, S. and Chitale, V. (2024). Decoding India's Changing Monsoon Patterns – A Tehsil Level Assessment. New Delhi: Council on Energy, Environment and Water. (Available online at: https://www.ceew.in/sites/default/files/decoding-how-climate-change-is-changing-monsoon-rainfall-patterns-in-india.pdf (accessed 19 June 2024).

Rangari, V.A., Bhatt, C.M. and Umamahesh, N.V. (2021). Rapid assessment of the October 2020 Hyderabad urban flood and risk analysis using geospatial data. *Current Science*, 120(12): 1840-1847. DOI: http://dx.doi.org/10.18520/cs/v120/i12/1840-1847.

Rao, G.V., Reddy, K.V., Srinivasan, R., Sridhar, V., Umamahesh, N.V. and Pratap, D. (2020). Spatio-temporal analysis of rainfall extremes in the flood-prone Nagavali and Vamsadhara Basins in eastern India. *Weather and Climate Extremes*, 29: 100265. DOI: https://doi.org/10.1016/j.wace.2020.100265.

Sharma, P.J., Loliyana, V.D., Resmi, S.R., Timbadiya, P.V. and Patel, P.L. (2018). Spatiotemporal trends in extreme rainfall and temperature indices over upper Tapi basin, India. *Theoretical and Applied Climatology*, 134: 1329-1354. DOI: https://doi.org/10.1007/s00704-017-2343-y.

Singh, G.P., Khole, M and Rase, D.M. (2015). Extreme Rainfall Events and Urban floods in the growing cities of India. *MAUSAM*, 66: 825-840. DOI: https://doi.org/10.54302/mausam.v66i4.592.

Subash, N., Sikka, A.K. and Ram Mohan, H.S. (2011). An investigation into observational characteristics of rainfall and temperature in Central Northeast India - a historical perspective 1889–2008. *Theor Appl Climatol*, 103: 305–319. DOI: https://doi.org/10.1007/s00704-010-0299-2.

Waghaye, A.M., Rajwade, Y.A., Randhe, R.D. and Kumari, N. (2018). Trend analysis and change point detection of rainfall of Andhra Pradesh and Telangana, India. *Journal of Agrometeorology*, 20(2): 160-163. DOI: https://doi.org/10.54386/jam.v20i2.532.

Authors' Declarations and Essential Ethical Compliances

Authors' Contributions (in accordance with ICMJE criteria for authorship)

Contribution	*Author 1*	*Author 2*
Conceived and designed the research or analysis	Yes	Yes
Collected the data	Yes	No
Contributed to data analysis & interpretation	Yes	Yes
Wrote the article/paper	Yes	No
Critical revision of the article/paper	Yes	Yes
Editing of the article/paper	Yes	Yes
Supervision	No	Yes
Project Administration	No	Yes
Funding Acquisition	No	No
Overall Contribution Proportion (%)	50	50

Funding
No financial support was received for the research and writing of this article.

Research involving human bodies or organs or tissues (Helsinki Declaration)
The author(s) solemnly declare(s) that this research has not involved any human subject (body or organs) for experimentation. It was not a clinical research. The contexts of human population/participation were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of Helsinki Declaration does not apply in cases of this study or written work.

Research involving animals (ARRIVE Checklist)
The author(s) solemnly declare(s) that this research has not involved any animal subject (body or organs) for experimentation. The research was not based on laboratory experiment involving any kind animal. The contexts of animals were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or ethical obligation of ARRIVE does not apply in cases of this study or written work.

Research on Indigenous Peoples and/or Traditional Knowledge
The author(s) solemnly declare(s) that this research has not involved Indigenous Peoples as participants or respondents. The contexts of Indigenous Peoples or Indigenous Knowledge were only indirectly covered through literature review. Therefore, prior informed consent (PIC) of the respondents or a Self-Declaration in this regard is not applicable for this article.

Research involving Plants
The author(s) solemnly declare(s) that this research has not involved the plants for experiment and field studies. Some contexts of plants are also indirectly covered through literature review. Yet, during this research the author(s) obeyed the principles of the Convention on Biological Diversity and the Convention on the Trade in Endangered Species of Wild Fauna and Flora.

Research Involving Local Community Participants (Non-Indigenous) or Children
The author(s) solemnly declare(s) that this research has not directly involved any local community participants or respondents belonging to non-Indigenous peoples. Neither this study involved any child in any form directly. The contexts of different humans, people, populations, men/women/children and ethnic people were only indirectly covered through literature review. Therefore, an Ethical Clearance (from a Committee or Authority) or prior informed consent (PIC) of the respondents or Self-Declaration in this regard does not apply in cases of this study or written work.

(Optional) PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses)
The author(s) has/have NOT complied with PRISMA standards. It is not relevant in case of this study or written work.

Competing Interests/Conflict of Interest
Author(s) has/have no competing financial, professional, or personal interests from other parties or in publishing this manuscript. There is no conflict of interest with the publisher or the editorial team or the reviewers.

Attribution and Representation
All opinions and mistakes are the author(s)' own and cannot be attributed to the institutions they represent. The publisher is also not responsible either for such opinions and mistakes in the text or graphs or images.

Rights and Permissions

Open Access. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this license, visit http://creativecommons.org/licenses/by/4.0/.

***

To see original copy of these declarations signed by Corresponding/First Author (on behalf of other co-authors too), please download associated zip folder [Declarations] from the published Abstract page accessible through and linked with the DOI: https://doi.org/10.33002/nr2581.6853.070211.